Faculty of Mechanical Engineering

CHARACTERISATION OF KENAF FIBRE REINFORCED ACRYLONITRILE BUTADIENE STYRENE COMPOSITES FOR FUSED FILAMENT FABRICATION

Syaza Najwa binti Mohd Farhan Han

Master of Science in Mechanical Engineering

2021

CHARACTERISATION OF KENAF FIBRE REINFORCED ACRYLONITRILE BUTADIENE STYRENE COMPOSITES FOR FUSED FILAMENT FABRICATION

SYAZA NAJWA BINTI MOHD FARHAN HAN

**A thesis submitted
in fulfilment of the requirements for the degree of
Master of Science in Mechanical Engineering**

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

DECLARATION

I declare that this thesis entitled "Characterisation of Kenaf Fibre Reinforced Acrylonitrile Butadiene Styrene Composites for Fused Filament Fabrication" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	……………………………..
Name	:	Syaza Najwa binti Mohd Farhan Han
Date	:	……………………………..

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature	:	…………………………………………
Supervisor Name	:	Dr. Mastura binti Mohammad Taha
Date	:	…………………………………………

DEDICATION

Specially dedicated to my beloved parents and siblings for their love, supports and prayers.

ABSTRACT

In this study, acrylonitrile butadiene styrene (ABS) polymer was reinforced with different percentages of kenaf fibres to produce fused filament fabrication (FFF) filaments. The degradation temperature, glass transition temperature (T_g), and melting temperature (T_m) of these newly developed filaments were evaluated via the thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). The rheological properties of these filaments were also investigated based on viscosity and shear rate. Then, the FFF technology was used to produce three-dimensional (3-D) printed parts with kenaf fibre-reinforced ABS (K-ABS) polymer composites with different kenaf fibre fractions to investigate the mechanical behaviours of these parts. Tensile and flexural testings were performed on these 3-D printed samples. In general, the degradation temperature of K-ABS polymer composites decreased, as the content of kenaf fibre in K-ABS composites increased. Meanwhile, the T_g and T_m of samples increased when the content of kenaf fibre in K-ABS composites increased from 0% to 5%. However, the further increment of kenaf fibre content from 5% to 10% in K-ABS composite decreased the T_g and T_m of composites. For rheological properties, the viscosity decreased with increasing shear rate, but with no apparent difference observed the viscosities for K-ABS composites with different percentages of kenaf fibre. Tensile strength and tensile modulus of K-ABS polymer composites decreased by 50.5% and 43.8% for K-ABS composites with kenaf content of 0% and 5%, respectively. The increasing content of kenaf fibre from 5% to 10% in K-ABS composites increased the tensile strength by 61.9% and tensile modulus by 49.4%. Flexural strength and flexural modulus decreased by 34.7% and 46.9% in K-ABS composites with kenaf fibre of 0% and 5%, respectively. Further addition of kenaf fibre in K-ABS from 5% to 10% increased the flexural strength and flexural modulus by 23.3% and 47.4%, respectively. The presence of porosity and poor interfacial adhesion between kenaf fibre and ABS matrix, as revealed in failure mode, may have caused the decrease of mechanical properties. Overall, K-ABS composite with 2.5% kenaf fibre was the best materials with better performance in the testing of thermal, rheological and mechanical properties and failure mode analysis. This research successfully demonstrated the capability of K-ABS composites with different kenaf fibre content serving as FFF filaments.

PENCIRIAN AKRILONITRIL BUTADIENA STIRENA KOMPOSIT BERTETULANG GENTIAN KENAF UNTUK FABRIKASI FILAMEN TERLAKUR

ABSTRAK

Dalam kajian ini, polimer akrilonitril butadiena stirena (ABS) diperkuatkan dengan pelbagai perkadaran gentian kenaf telah diguna untuk menghasilkan filamen untuk fabrikasi filamen terlakur (FFF). Suhu degradasi, suhu peralihan kaca (T_g) dan suhu lebur (T_m) bagi filamen yang baru disintelesis ini telah dinilaikan dengan analisis termogravimetri (TGA) dan kalorimetri pengimbasan perbezaan (DSC). Sifat reologi untuk filamen baru ini juga disiasat berdasarkan kelikatan dan kadar ricih. Kemudian, teknologi FFF digunakan untuk menghasilkan bahagian cetakan tiga dimensi (3D) bagi polimer komposit ABS bertetulang gentian kenaf (K-ABS) dengan perkadaran gentian kenaf yang berlainan, untuk menyiasat perlakuan mekanikal sampel cetakan ini. Ujian tegangan dan ujian lenturan dijalankan untuk menyiasat sifat tegangan dan sifat lenturan bagi sampel cetakan 3D. Secara am, suhu degradasi polimer komposit K-ABS menurun dengan peningkatan kandungan gentian kenaf. Sementara itu, T_g dan T_m bagi polimer komposit K-ABS dengan 0% sehingga 5% gentian kenaf meningkat, manakala, peningkatan kandungan gentian kenaf daripada 5% sehingga 10% telah menurunkan T_g dan T_m untuk komposit. Bagi sifat reologi, kelikatan menurun dengan peningkatan kadar ricih, kemudian, tidak ada perbezaan yang ketara di kalangan kelikatan polimer komposit K-ABS dengan perkadaran gentian kenaf yang berlainan. Kekuatan tegangan dan modulus tegangan untuk polimer K-ABS menurun daripada 0% kepada 5% kandungan gentian kenaf dengan 50.5% dan 43.8% masing-masing. Peningkatan kandungan gentian kenaf daripada 5% kepada 10% telah meningkatkan kekuatan tegangan dan modulus tegangan masing-masing dengan 61.9% dan 49.4%. Kekuatan lenturan dan modulus lenturan untuk polimer komposit K-ABS menurun daripada 0% kepada 5% dengan 34.7% dan 46.9% masing-masing. Lanjutan tambahan gentian kenaf daripada 5% kepada 10% telah meningkatkan kekuatan lenturan dan modulus lenturan masing-masing dengan 23.3% dan 47.4%. Analisis ragam kegagalan menunjukkan kehadiran keliangan dan pelekatan antara muka di antara gentian kenaf dan matriks ABSs membawa kepada penurunan sifat mekanikal. Secara keseluruhan, polimer komposit ABS bertetulang 2.5% gentian kenaf merupakan kandungan terbaik kelebihan prestasi dalam analisa terma, reologi, Mekanikal dan ragam kegagalan. Kajian ini telah menunjukkan keupayaan ABS polimer komposit K-ABS dengan perkadaran gentian kenaf yang berlainan sesuai dijadikan filament FFF.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful.

Alhamdulillah, all praise to Allah, the almighty for granting me the strength and blessing in completing this thesis. First and foremost, I would like to express my special appreciation to my supervisor and co-supervisor, Dr. Mastura binti Mohammad Taha and Dr. Muhd Ridzuan bin Mansor for their guidance, supervision, support and encouragement throughout the completion of the research. I also would like to thank Universiti Teknikal Malaysia Melaka and Kementerian Pendidikan Tinggi Malaysia for the grant research.

My deepest gratitude and grateful goes to my parents, Mohd Farhan Han bin Abdullah and Rohanita binti Abdul Manap, and my beloved siblings for all of their sacrifices, prayers and supports throughout my years of study. My sincere appreciation also extends to technicians from Universiti Teknikal Malaysia Melaka and Universiti Kuala Lumpur Malaysian Institute of Chemical and Bioengineering Technology for their assistance and guidance in the laboratories. Furthermore, my appreciation goes to my colleague who had involved directly or indirectly throughout this research journey.

Last but not least, I would like to thank my partner in crime for his encouragement and understanding my journey in completing this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

%	-	Percentage
°C	-	Degree Celsius
°C/min	-	Degree Celsius per minute
.STL	-	Standard triangulation language
2D	-	Two-dimensional
3D	-	Three-dimensional
ABS	-	Acrylonitrile butadiene styrene
Al_20_3	-	Aluminium oxide
AM	-	Additive manufacturing
ANOVA	-	Analysis of varience
AP	-	(3-aminopropyl) triethoxysilane
ASTM	-	American Society for Testing and Materials
β-TCP	-	Beta tricalcium phosphate
BBD	-	Box-Behnken Design
CAD	-	Computer-aided design
cm	-	Centimetre
CFF	-	Composite filament fabrication
CFRP	-	Carbon fibre reinforced thermoplastic composites
DMA	-	Dynamic mechanical analysis
DSC	-	Differential Scanning Calorimetry
DTA	-	Differential thermal analysis
EBM	-	Electron beam melting
FDM	-	Fused deposition modelling
FFF	-	Fused filament fabrication
FML	-	Fibre metal laminate
FRP	-	Fibre reinforced plastics
GFPP	-	Glass fibre reinforced polypropylene composites
GP	-	(3-glycidyloxypropyl) tri-methoxysilane

GPa	- Gigapascal
g/cm^3	- Density
HDPE	- High-density polythene
HPT	- High processing temperature
HYP	- High yield fibre
Hz	- Frequency
IPMC	- Ionic polymer-metal composites
JFTRP	- Jute fibre reinforced thermoplastic composites
kN	- Kilo Newton
kW	- Kilo watt
LDPE	- How-density polythene
LMP	- Laser metal deposition
LOM	- Laminated object manufacturing
LPT	- Low processing temperature
mm	- Millimetre
mm/min	- Millimetre per minute
m	- Metre
MA	- (3-trimethoxysilyl) propyl methacrylate
MAPE	- Maleated polythene
MH	- Magnesium hydroxide
MJM	- Multi-jet modelling
MPa	- Megapascal
N	- Newton
NFC	- Natural fibre composites
NFPC	- Natural fibre reinforced polymer composites
OH	- Hydroxyl
OMMT	- Organic montmorillonite
PA	- Polyamide
PC	- Polycarbonate
PE	- Polythene
PF	- Palm fibre
PHA	- Polyhydroxyalkanoate

PJP	-	Plastic jet printing
PLA	-	Polylactic acid
PP	-	Polypropylene
PP-g-MA	-	Polypropylene grafted maleic anhydride
PV	-	Measured value
r-PA	-	Recycled polyamide
r-PET	-	Recycled polythene terephthalate
r-PP	-	Recycled polypropylene
RP	-	Rapid prototyping
rpm	-	Revolution per minute
RSM	-	Response surface methodology
s^{-1}	-	Per second
SEM	-	Scanning electron microscopy
SLA	-	stereolithography
SLM	-	Selective laser melting
SLS	-	Selective laser sintering
SV	-	Set value
T_g	-	Glass transition temperature
T_m	-	Melting temperature
TG	-	Thermogravimetric
TGA	-	Thermogravimetric analysis
TMA	-	Thermomechanical analyser
TPF	-	Treated palm fibre
TPU	-	Thermoplastic polyurethane
µm	-	micrometre
V_f	-	Volume fraction
WPC	-	Wood flour polypropylene composites
wt%	-	Weight percentage
xGnPs	-	Graphene nanoplatelets

LIST OF PUBLICATIONS

JOURNAL:

1. Han, S. N. M. F., Taha, M. M., and Mansor, M. R., 2019. Thermal and melt flow behaviour of kenaf fibre reinforced acrylonitrile butadiene styrene composites for fused filament fabrication. *Defence S&T Technical Bulletin*, 12(2), pp. 238-246.

PROCEEDING:

1. Syaza Najwa Mohd Farhan Han, Mastura Mohammad Taha, Muhd Ridzuan Mansor, Muhammad Mufqi Aminallah. 2019. Thermal Degradation Study of Acrylonitrile Butadiene Styrene (ABS) Composites for FFF. *Proceedings of Mechanical Engineering Research Day (MERD 2019)*. Melaka, Malaysia, pp. 3-4, August 2019.

ACCEPTED:

1. Farhan Han, S. N. M., Mastura, M. T., Mansor, M. R., and Abdul Kudus, S. I. Weighting the material requirements of NFRC by using Fuzzy AHP with extent analysis. *Journal of Advanced Manufacturing Technology (JAMT)*. To be published.

CHAPTER 1

INTRODUCTION

1.1 Background of study

The manufacturer, researcher and society are currently facing the issues with traditional manufacturing process in terms of economically convenient and less wasteful materials production (Tekinalp et al., 2014; Ford and Dispeisse, 2016). Additive manufacturing (AM) process has been introduced and developed to overcome the problem regards material wastefulness and easy to handle (Mani et al., 2014; Chen et al., 2015). A low cost material to market and reduce time for new innovations are the benefits to looking forward (Leigh et al., 2012). Besides, an environmentally friendly material is crucial nowadays in developing products for industries (Thakur et al., 2014). However, the AM process mainly used material is thermoplastics polymer, hence, natural fibre reinforced polymer composites material is one of the limitation for AM process.

Fused filament fabrication (FFF) or three-dimensional (3D) printer is one of additive manufacturing (AM) technologies. FFF technology has been used widely and it is the most significant technique for AM based on the capability of FFF to print 3D objects. The availability of feedstock for FFF technique is the main limitation for industrial applications since FFF mainly used material is thermoplastic polymer. The thermoplastic polymer is widely used as the feedstock for FFF since it is safe to an environment (Torres et al., 2016). As FFF develop well and the range of feedstock becomes wider, material used other than thermoplastic are fibre reinforced composite. Parandoush and Lin (2017) stated that currently, researches tend to developed filament with short fibre additives for FFF technology. However, there are still deficiency in research and knowledge when it comes to feedstock material for FFF (Mohan et al., 2017).

Nowadays, natural fibre composites are developed well as it is environmentally friendly material and various types of natural fibre have been investigated for composites including kenaf, hemp, banana and flax (Kant et al., 2017). The characteristics of natural fibre such as high strength, low cost and biodegradable are one of the reasons it becomes an alternative to synthetic fibre and widely used in industries due to its lightweight and environmental aspects (Ahmad et al., 2015). In addition, Ahmad et al., (2015) also stated that natural fibre can be used as reinforcement for thermoset or thermoplastics instead of synthetic fibres. Besides, natural fibre composites are renewable, thus it has high potential to lower environmental burden of the fibre portion of the composite material (Boland et al., 2016). Kenaf fibre is abundantly available in Malaysia and used as reinforcement for its good mechanical properties. The combination of kenaf fibre and acrylonitrile butadiene styrene (ABS) polymer will greatly give advance and enhancement in this field. Hence, kenaf fibre reinforced ABS polymer composites filament are studied to broad the materials used and develop for FFF technology.

Given that the filament used for the FFF process will need to be thermally controlled for successful printing of the desired design, thus, the thermal property of the materials used for developing new FFF composites will need to be carefully evaluated (Mohan et al., 2017). The same can be said on the rheological property of the materials used, which will determine the viscosity of the composite filaments. Besides, the strength of the composite materials is dependent on the mechanical properties of fibres such as tensility and flexure, while the fractures will need to be carefully assessed via failure mode analysis during mechanical testing in developing new FFF composite materials.

In this study, composites with different volume percentage of kenaf fibre reinforced ABS polymer (K-ABS) fibre were fabricated through a twin-screw extruder to form composite filaments. The thermal properties of these K-ABS filaments were evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) while the flow behaviour of filaments with different volume percentage of K-ABS composites was investigated using capillary rheometer. Also, their tensility and flexure were assessed via mechanical testing, while surface fractures of the composites were examined via failure mode analysis. Finally, the effect of kenaf fibre loading, i.e., the proportion of fibres added, on thermal properties, rheological behaviour, mechanical properties, and failure mode analysis were quantified.

1.2 Problem Statement

Identification of the problem is performed while investigating the market needs on concern towards environmentally friendly materials in product development using FFF technology. Currently, synthetic thermoplastic polymers such as ABS and polylactic acid (PLA) are commonly used for FFF technology at relatively high cost while generating hazardous wastes to the environment. To address these issues, composites of K-ABS were studied as a potential alternative for FFF technology. Kenaf fibre was chosen for this study because it contains different type of resins with good mechanical attributes comparable to other natural fibre for strengthening the FFF composites. Equally important, it is widely available in Malaysia, safe for handling, relatively low in production cost, and biodegradable, making it suitable for large-scale industrial applications (Ahmad et al., 2015).

However, adding natural fillers into polymer poses two disadvantages, namely low thermal stability and low chemical compatibility. Besides, knowledge on melt flow behaviour is required to understand the influence of natural fibre with thermoplastic polymer. Navarrete et al., (2018) stated that the thermal stability of natural fibre reinforced polymer composites (NFPC) is vital for identifying the safe zone of processing temperature for FFF. As FFF technology is based on material extrusion, the rheology and mechanical properties of 3D printed material are closely related to the physical characteristics of NFPC. The processing performance of NFPC, such as filler and chemical structure, would thus affect the flow properties and the 3D printed materials (Sanchez et al., 2019). Therefore, investigation on the strength and fracture mode of the composites via failure mode analysis becomes indispensable.

1.3 Objectives

The study investigated the characterisation of kenaf fibre reinforced ABS composites for FFF. The specific objectives of this study were as follows:

i. To investigate the effect of various loading of kenaf fibre reinforced ABS polymer composites on thermal, rheological and mechanical properties.

ii. To examine surface fractures of the 3D samples printed with FFF composites comprising K-ABS with different kenaf fibre loadings via failure mode analysis.

1.4 Scope of study

The scope of the present research encompassed the investigation of the thermal, rheological and mechanical properties of composites comprising K-ABS polymer with different proportions of kenaf fibres, and fabricated into FFF filaments. In between, a twin-screw extruder was used to fabricated different volume percentage of kenaf fibre reinforced ABS polymer composites into filament form with diameter 1.75 mm ± 0.07 mm. Different volume percentage of kenaf fibre used were 0%, 2.5%, 5%, 7.5% and 10%. Then, thermal test was conducted to investigated the degradability of different loadings of kenaf fibre reinforced ABS composites using TGA with standard used is ASTM E1131, whereas the glass transition temperature and melting temperature were investigated using DSC with standard used is ASTM D3418. Furthermore, investigation on rheological properties using capillary rheometer with standard ASTM D3835 to identify the viscosity of samples via shear rate. FFF technology, which is 3D printer, was used to fabricated 3D printed samples. Then, mechanical properties of 3D printed K-ABS composite filaments was identified by conducting tensile test and flexural test using standard ASTM D638 and ASTM D790 respectively. Finally, the failure mode analysis was conducted via the scanning electronic microscopy (SEM).

1.5 Chapter outline

This thesis is structured into five chapters. The first chapter is the introduction followed by Chapter 2, which presents a comprehensive literature review on relevant areas associated with this study while Chapter 3 deliberates the methodology used in this research. The methodology chapter encompasses the deliberation on the structure of the research works, including the fabrication of commercialised ABS, the preparation of K-ABS composites with various proportions of kenaf fibre, and experimental testing on thermal,